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INVESTIGATION OF MICROWAVE BACKSCATTER FROM THE AIR-SEA INTERFACE

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Prof. Robert E. McIntosh
James R. Carswell
Department of Electrical and Computer Engineering
Knowles Engineering Building
University of Massachusetts
Amherst, MA 01003

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Goals

To better understand the backscatter of microwave signals from the ocean surface and its relationship to the processes occurring at the air-sea interface.

Overview

Monitoring the ocean surface winds and mean ocean surface level is essential for improving our knowledge of the climate. Two instruments that may provide us with this information are satellite-based scatterometers and altimeters. However, these instruments measure the backscatter characteristics of the ocean surface from which other physical parameters, such as the wind speed or ocean surface height, are derived. To improve the algorithms or models that relate the electromagnetic backscatter to the desired physical parameters, the University of Massachusetts (UMass) Microwave Remote Sensing Laboratory (MIRSL) designed and fabricated three airborne scatterometers: a C-band scatterometer (CSCAT), Ku-band scatterometer (KUSCAT) and C/Ku-band scatterometer (EMBR). One or more of these instruments participated in the Electromagnetic Bias experiment (EM Bias), Shelf Edge Exchange Processes experiment (SEEP), Surface Wave Dynamics Experiment (SWADE), Southern Ocean Wave EXperiment (SOWEX), Hurricane Tina research flights, Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) and Ladir In-space Technology Experiment (LITE). This document describes the three scatterometers, summarizes our measurement campaigns and major contributions to the scientific and engineering communities, lists the publications that resulted and presents the degrees earned under the support this NASA grant.

Instrument Descriptions

CSCAT

CSCAT was designed and fabricated at the Microwave Remote Sensing Laboratory (MIRSL) with the support of NASA. Table 1 lists its specifications and a description of the antenna system, transmitter/receiver and data acquisition system is given below. A complete de-

scription of CSCAT was published in the March, 1991 issue of the IEEE Transactions on Geoscience and Remote Sensing [1].

Antenna System

The antenna/spinner module consists of a microstrip planar array, spinner assembly and shaft encoder. The array is laminated to a 48-inch aluminum plate and a shaft is mounted on the other side. The shaft fits up through the bearing housing of the spinner assembly. The antenna's pointing angle is frequency steered from 20° to 50° off boresight (incidence) by changing the transmit frequency from 5.73 GHz to 5.01 GHz, and the spinner mechanically rotates the antenna in azimuth at speeds up to 30 rpm, providing contiguous azimuthal coverage of the surface winds. A 10-bit shaft encoder monitors the position of the antenna and sends the information to the data acquisition system. Figure 1 displays this conical scanning technique.

Transmitter/Receiver and Data Acquisition Systems

The antenna module is connected to the transmitter/receiver module through a rotary joint and a low-loss microwave coaxial cable. The transmitter/receiver module is made up of a commercial solid state C-band amplifier and a temperature-controlled transmitter and receiver. The transmitter mixes a 30 MHz IF signal with a local RF oscillator of frequency 4.98 GHz to 5.7 GHz. This signal is pulse modulated, amplified to either 100 mW or 10 W, and routed to the antenna module via the coaxial cable. The pulse duration and the power level is set by the digital interface module, which creates the control signals as well as the pulse repetition frequency, the receive signal and the receiver bandwidth selection signal. All these signals are programmable over a 16-bit bus between the digital interface module and the computer.

The two control signals, receiver and receiver bandwidth selection, determine the mode and configuration of the receiver. The receive control signal enables the first stage of the receiver, which amplifies, filters and down-converts the return signal from the antenna module. The down converted signal or IF signal is amplified and passed through one of 5 bandpass filters ranging from 50 KHz to 10 MHz. This filter bank is designed to maintain a minimum

PARAMETER	UMASS C-SCAT	UMASS KUSCAT	UMASS EMBR
FREQUENCY (GHz)	4.97-5.70	12.89-14.9	5.3 / 13.6
POLARIZATION	VV	VV	VV
INCIDENCE (degrees)	20-50	20-50	Nadir
AZIMUTH (degrees)	0-360	0-360	0-360
SCAN RATE (rpm)	0-30	0-120	1-5
PEAK POWER (watts)	.1 or 10	.2 or 20	.05
ANTENNA GAIN (dB)	26 to 29	25 to 28	31.22 / 41.65
BEAM WIDTH (degrees)	4.2-6.3	4-6.3	3.2 / 1.4
PRF (KHz)	0.1-2	0.1-30	.01-6
PULSE WIDTH (μ sec)	.2-120	.2-120	.08-160
RECEIVER BAND WIDTH (MHz)	.1-10	.05-20	7
DETECTION	Logarithmic	Logarithmic	Logarithmic

Table 1: Radar Specifications.

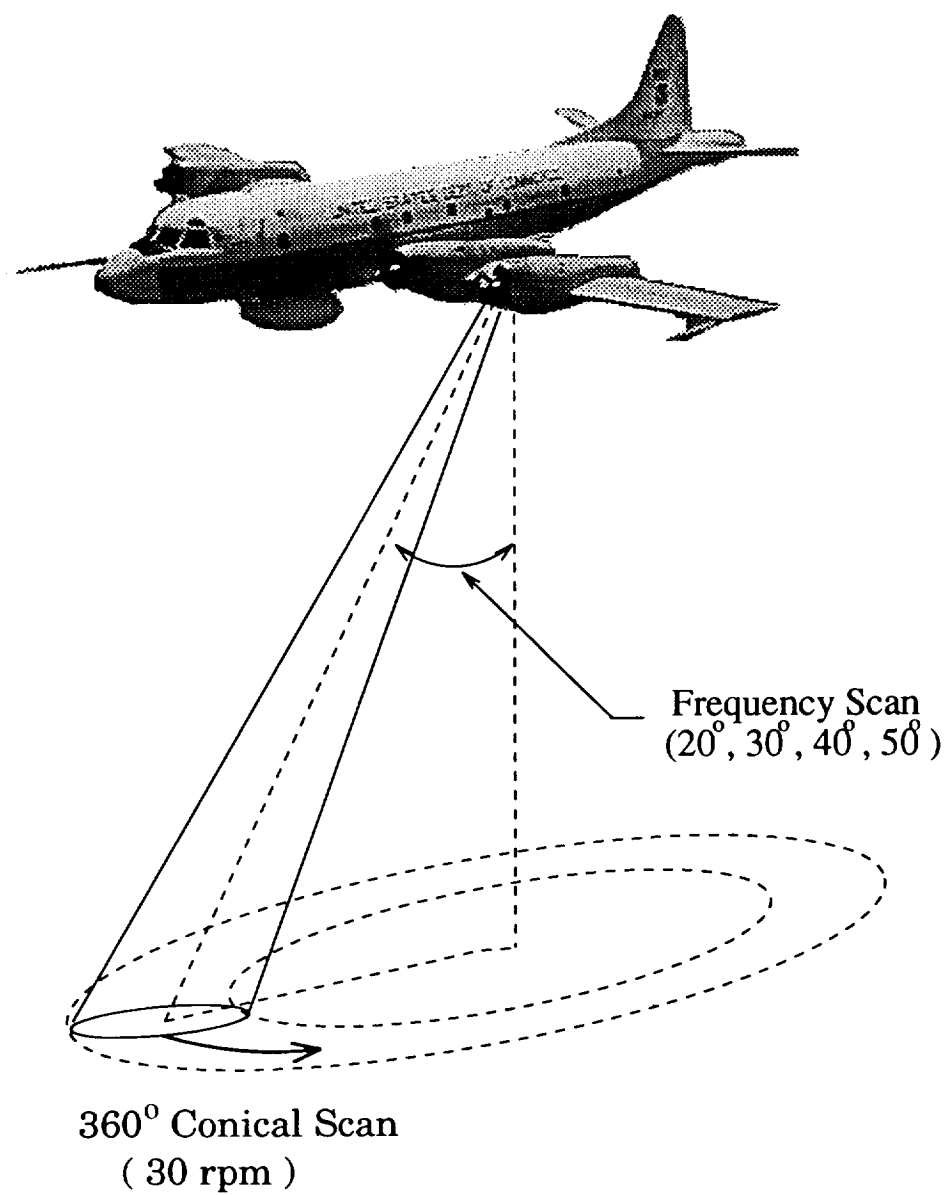


Figure 1: Conical scanning technique implemented by CSCAT.

signal to noise ratio (SNR) with altitude; that is, the transmit pulse length increases with increasing altitude, so that a narrower bandpass filter can be selected to compensate for the decrease in P_R [2]. The receiver bandwidth selection signal selects the filter approximately 3 to 8 times the bandwidth of the transmitted pulse.

A 85 dB dynamic range log detector follows the filter bank. This detector linearly maps the input IF power (in dBm) to a voltage, which is held by a sample and hold circuit. The output of this circuit is connected to a 12-bit A/D card in the computer/data acquisition module that digitizes this signal. The 12-bit representation of the detected power level is stored to disk along with the 10-bit encoder word. The radar system parameters and the navigation data, which provides information about altitude, pitch, yaw, roll, latitude and longitude, are also stored to disk.

A calibration loop monitors fluctuations in the gain of the transmitter and receiver. This loop attenuates a replica of the transmitted pulse and couples it back into the receiver, where it is detected and its power level stored to disk. The receiver gain is monitored separately by recording the noise floor of the instrument. During a flight the gains typically vary by only 0.1 dB.

Installations

CSCAT has been installed on two aircraft: the NASA Ames C-130b and the NOAA N42RF P3. The C-130b was flown in SWADE and the P3 was flown in ERS-1 Underflights, Hurricane Tina and TOGA COARE. To ensure the accuracy of our measurements, CSCAT was calibrated, before and after each installation, at the University of Massachusetts using a 1-m trihedral corner reflector. The cables and connectors used in the installations were also used during the calibrations to ensure all losses to the antenna are measured.

KUSCAT

KUSCAT was designed and fabricated at MIRSL with the support of NASA. Its design is similar to CSCAT, however, its data acquisition/control module has been upgraded to allow the instrument to rapidly hop through four incidence angles (20°, 30°, 40° and 50°). These modifications are described below, and KUSCAT's general specifications are given in Table 1.

Antenna System

The antenna is a frequency scaled version of the CSCAT antenna. Its pointing angle can be frequency scanned from 20° to 50° incidence by changing the transmit frequency from 14.8 GHz to 12.8 GHz. The spinner module design is the same as the CSCAT spinner, but can rotate the antenna in azimuth at a higher rate, 120 rpm.

Transmitter/Receiver

The basic design of the transmitter/receiver module follows that of CSCAT's. The differences are that the RF section is at Ku-band, and a 20-W TWT amplifier was used to amplify the transmit pulse. Additionally, the transmit/receive switches, internal calibration loop and a low-noise amplifier are in a temperature controlled front-end box that can be located near the antenna. This improves the signal-to-noise ratio by approximately 3 dB.

Rapid Incidence Angle Scanning

The data acquisition/control unit has been upgraded to include a scanning incidence angle mode. In this mode, the transmit frequency is switch from pulse to pulse between the four frequencies that correspond to 20°, 30°, 40° and 50° incidence. At the same time, the PRF is increased by a factor of four times the rate at which independent samples for a single incidence angle occur. In this manner, the maximum number of independent data samples are obtained at all four angles simultaneously, as the aircraft is following its flight line. Figure 2 illustrates this scanning technique.

Installation

KUSCAT was installed on the NASA Wallops Flight Facility (WFF) research P3 for LITE, and was calibrated at the University of Massachusetts using a 0.5-m trihedral corner reflector. The cables and connectors used in the P3 installation were also used during the calibration to ensure all losses to the antenna were measured.

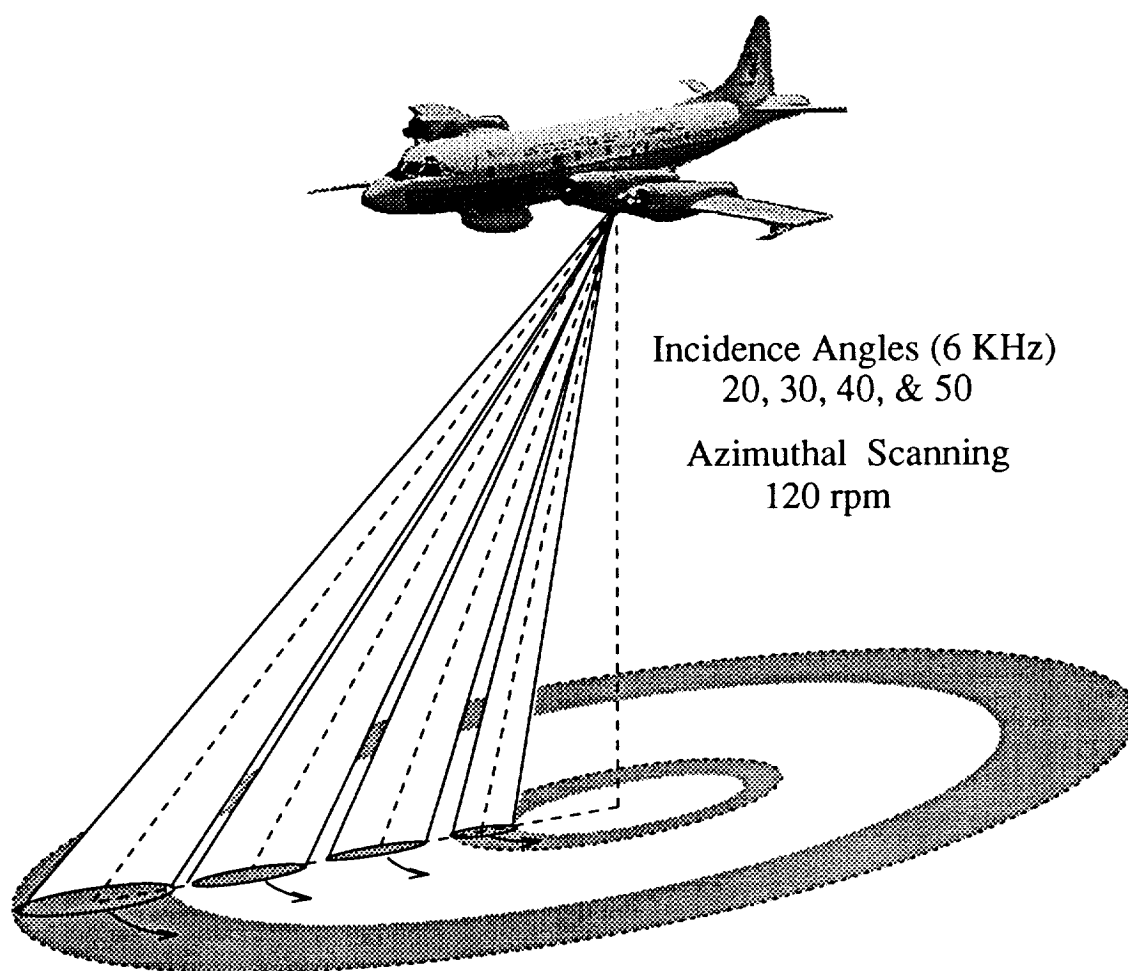


Figure 2: Conical scanning technique with rapid incidence angle switching implemented by KUSCAT.

EMBR

EMBR was designed and fabricated at MIRSLS with the support of NASA. It participated in EM Bias experiment, SEEP experiment, SWADE and SOWEX to study the electromagnetic bias (em-bias) of the ocean surface at 5.3 GHz and 13.6 GHz, the frequencies of the TOPEX/POSEIDON altimeters. The general description of the antenna and transmitter/receiver systems of this dual-frequency pulsed scatterometer are given below, and EMBR's specifications are summarized in Table 1.

Antenna System

EMBR was equipped with a nadir-looking dual-frequency parabolic reflector antenna in SWADE (the same that was used with CSCAT in the EM Bias and SEEP experiments), and with two smaller nadir-looking antennas for SOWEX. The question of possible polarization effects was raised before SWADE, therefore the dual-frequency antenna was installed with a spinner on the NASA WFF research P3 aircraft. It was 1.2 m in diameter with a gain of 31 dB at 5.3 GHz and 41 dB at 13.6 GHz, and had a cross-pol isolation greater than 25 dB. Since polarization effects were not detected in SWADE and the Australian Fokker-27 aircraft had limited room for the scatterometer antennas, the dual-frequency reflector antenna was replaced by a Ku-band horn and a C-band microstrip patch antenna for SOWEX.

Transmitter/Receiver System

The transmitter/receiver has single-frequency and dual-frequency operating modes, in the latter, the frequency is switched between transmitting pulses. In either case, a 30 MHz IF signal is mixed up with a local RF oscillator, 5.27 GHz or 14.57 GHz, and pulsed with the transmitter pin-diode switch. The pulse length is programmable between 80 nsec to 160 usec. The up-converted signal is amplified to 50 mW and sent to the antenna via semi-rigid coaxial cable. The received signal is directed from the antenna to the receiver chain that amplifies and down-converts it to the 30 MHz. The down-converted signal is passed through a 7 MHz bandpass filter and detected using a log detector with 80 dB dynamic range. The video output is sent to a 12-bit A/D converter and store to disk. An HP 9000/330 computer controls the A/D, transmit pulse length and PRF. To achieve a system precision of 0.2 dB,

the transmitter/receiver is enclosed in a temperature stabilized housing, and the system gain is monitored through an internal calibration loop.

Installations

EMBR was installed on two aircraft: the NASA WFF research P3 and the Australian Fokker-27. The P3 was flown in the EM Bias experiment, SEEP experiment and SWADE, while the Fokker-27 was flown in SOWEX. EMBR was calibrated after each experiment at the University of Massachusetts using a 0.5-m trihedral corner reflector.

Experiments and Major Contributions

CSCAT Measurements

To investigate C-band off-nadir ocean backscatter and its relationship to the air-sea processes, CSCAT was flown in the four experiments: SWADE, ERS-1 Underflights, Hurricane Tina and TOGA COARE. A brief description of each experiment is given below, and the primary results are summarized.

SWADE, which began in October 1990 and lasted for six months, was sponsored by the Office of Naval Research (ONR). The experiment's primary location was off the coast of Virginia, where several National Oceanographic and Atmospheric Administration's (NOAA) buoys were deployed. These buoys measured wind speed, wind direction, pressure, air temperature, sea temperature, significant wave height and directional or non-directional wave spectra. CSCAT was flown on the NASA Ames Research Center C130B, which flew ten missions from 27 February, 1991 to 10 March, 1991. Jet Propulsion Laboratory's (JPL) Ku-band scatterometer, NUSCAT, was also flown on this aircraft. The two instruments collected over fifty hours of C- and Ku-band backscatter measurements.

From these data, two significant discoveries were made: the backscatter measurements increased in the presence of large waves and low winds, and the azimuthal modulation of the backscatter was an order of magnitude greater than predicted by CMOD4 and SASS-II model functions for low-wind conditions. The first discovery was published in the May, 1995 issue of the IEEE Transactions on Geoscience and Remote Sensing [3]. Collaborating with

Fuk Li and his colleagues at JPL, we analyzed cases from the SWADE data set, where C- and Ku-band backscatter measurements were obtained under similar winds, but different significant wave heights (SWH). For moderate winds (7 to $15 \text{ m}\cdot\text{s}^{-1}$), the backscatter did not depend on SWH, however under low-wind conditions (3 to $6 \text{ m}\cdot\text{s}^{-1}$), the backscatter was enhanced by several dB as the SWH increased from 1 m to 6 m . This clearly demonstrated that the backscatter did not solely depend on the wind speed for low-winds conditions. We argued that the enhanced backscatter may be better explained by examining its relationship to frictional velocity. Frictional velocity measurements, obtained under low-wind conditions, showed increased values for high-SWH cases compared to low-SWH cases. Unfortunately, these measurements were not colocated, and therefore determining the correlation between the frictional velocity and backscatter measurements was not possible. However, a qualitative argument was put forth. Using Plant's composite surface model, which relates the backscatter to frictional velocity, the increase in the predicted backscatter values, due to the measured increase in the frictional velocity measurements for high-SWH compared to low-SWH conditions, was equivalent to the increase in our backscatter measurements for similar conditions. Therefore a model relating the backscatter to frictional velocity may better predicted the backscatter values under low-wind conditions.

We also found the azimuthal modulation of the backscatter, with respect to the wind direction, was an order of magnitude greater than predicted by the operational C-band model, CMOD4, and the Ku-band model, SASS-II, for winds less than $5 \text{ m}\cdot\text{s}^{-1}$. These results were published in Steve Carson's dissertation [4] and the IEEE Proceedings Special Issue on Remote Sensing. Comparing the measurements with the Donelan and Pierson composite surface model (DP87), we found qualitative agreement between the measurements and DP87. This model predicts that the crosswind backscatter will decrease at a faster rate than the upwind backscatter as the wind speed decreases. Therefore, the azimuthal modulation will increase as the wind decreases. It also predicts that the rapid decrease in the backscatter is due to viscous dampening of the capillary-gravity waves. As the wind decreases, these waves will be suppressed, and therefore, Bragg scattering will cease to contribute to the backscatter. However, due to the limited number of low-wind cases sampled, we could not verify this rapid decrease, though our measurements supported to this concept.

Following SWADE, CSCAT was installed on the NOAA N42RF P3, and flown in a series of flights over the Gulf of Mexico that coincided with C-band backscatter measurements by the ERS-1 AMI scatterometer. Six missions were flown between 12 November, 1991 to 6 December, 1991 when cold-air outflows over the Gulf occurred. Under these conditions the air temperature is colder than the sea surface temperature, causing increase turbulence in the lower boundary layer. The underflights were designed to investigate the effects of these unstable atmospheric conditions at the air/sea interface on the backscatter measurements obtained by CSCAT and the AMI scatterometer.

Analysis of the measurements showed good agreement between CSCAT and the AMI scatterometer for five out of the six flights. During these five flights, slightly unstable conditions were encountered with Z/L values as large as -2 . The Z/L value is the Monin Obukhov parameter, which quantifies the stability of the boundary layer using the sea surface temperature, air temperature and near-surface wind speed. Negative values would indicate unstable conditions (increased turbulence), while positive values would indicate stable conditions (increased stratification). The one mission where agreement was poor, the wind was less than 2 m/s and unstable conditions existed, $Z/L = -8$. We believe the poor agreement was due to sampling differences. The wind field within the AMI swath varied substantially with gusts on the order in magnitude of twice the wind speed. CSCAT, however, covered an area much smaller making it less susceptible to the variability in the wind field for a given measurement. Therefore, it was not surprising that the measurements from the two instruments differed from each other in these conditions. Determining whether the difference was due to stability or low-wind conditions could not be determined from these flights alone due to the limited number of conditions sampled and coincident measurements gathered. Working with John Wilkerson, we presented these results at the MeteoFrance Specialty Meeting on Airborne Radars and Lidars [5] and the ERS-1 Geophysical Validation Workshop [6]. These results were also published in Steve Carson's dissertation.

In September 1992 the NOAA Hurricane Research Center (HRD) sponsored a series of flights through Hurricane Tina, which was centered off the west coast of Mexico at approximately 12°N and 107°W . The NOAA P3 aircraft, N42RF and N43RF, flew several missions through the eye of this hurricane. With support from NASA and NOAA, CSCAT was

installed on N42RF and participated in these missions. The UMASS Stepped Frequency Microwave Radiometer (SFMR) was also installed on N42RF and provided estimates of the rain rate and wind speed. CSCAT collected backscatter measurements under wind conditions exceeding $30 \text{ m}\cdot\text{s}^{-1}$ at the surface. Approximately 30 hours of data were obtained.

These flights demonstrated, for the first time, that a combined active/passive C-band airborne system could retrieve accurate estimates of the near-ocean surface wind vector and precipitation through a hurricane. The radiometer provided wind speed and rain rate estimates, while the scatterometer provided wind direction and a second estimate on the wind speed. In our paper published in the IEEE Proceedings Special Issue on Remote Sensing [7], we compared our backscatter measurements with CMOD4 predicted values using SFMR wind speed estimates. CMOD4 over predicted the backscatter for winds greater than $20 \text{ m}\cdot\text{s}^{-1}$, especially in the upwind direction. Furthermore, the measurements indicated that the upwind backscatter may saturate with increasing winds above $25 \text{ m}\cdot\text{s}^{-1}$. Future collaboration with HRD, who has obtained C-band backscatter measurements for winds greater than $50 \text{ m}\cdot\text{s}^{-1}$ with a similar scatterometer, will answer whether a saturation wind speed exists.

In addition, Paylor showed that the backscatter measurements also decrease in the presence of precipitation [8]. The measurements were corrected for two-way attenuation due to the precipitation, therefore the decrease in the backscatter is most likely due to effects the rain has on the surface. One hypothesis proposed is the rain dampens the capillary-gravity waves resulting in a reduction in the the backscatter. This has been observed previously, but our measurements are the first high resolution measurements made in the open ocean and accompanied by accurate coincident wind speed and precipitation estimates. Once again, we are collaborating with HRD to determine to what extent the precipitation affects the backscatter, and are presenting preliminary results at the International Geoscience and Remote Sensing Conference in Florence Italy in July of 1995.

CSCAT's last deployment was TOGA COARE, which was organized by the TOGA COARE International Project Office at the University Center for Atmospheric Research (UCAR). This experiment consisted of four intensive operation periods (IOP) beginning on 1 November, 1992 and ending on 22 February, 1993. The primary area for this experiment was the warm pool region in the South Pacific ocean bounded by 0° to -10° latitude and 140°

to 160° longitude. Several buoys were deployed by the NOAA Pacific Marine Environmental Laboratory (PMEL) and Woods Hole Oceanographic Institution (WHOI), providing in situ measurements of the wind vector, air temperature, sea surface temperature, humidity and pressure. CSCAT was flown on the NOAA N42RF P3 which flew twenty-two missions during the four IOPs. Over 120 hours of C-band backscatter measurements were collected, half under wind conditions less than $5 \text{ m}\cdot\text{s}^{-1}$.

From these low-wind speed backscatter measurements, we investigated their functional dependence on wind speed. We found that the traditional power-law relationship between the wind speed and the backscatter does not describe the measurements for winds less than $5 \text{ m}\cdot\text{s}^{-1}$. This was previously shown in wave tank studies by Plant, however our analysis goes a step further and demonstrates that a power-law relationship, whether it's with wind speed or wind stress or frictional velocity, cannot describe the backscatter response under low-wind conditions. This result is important to many investigators now developing empirical models that relate the backscatter to frictional velocity instead of wind speed. If they use a power law and include wind conditions under $5 \text{ m}\cdot\text{s}^{-1}$, they will over estimate the sensitivity of the backscatter to frictional velocity.

The backscatter measurements were also compared to the CMOD4 model. For moderate winds, they agreed well. The mean difference between the measured values and CMOD4 was less than 0.25 dB for 30°, 40° and 50° incidence. At low winds, however, the measurements significantly departed from the predicted CMOD4 response. That is, they exhibited a much more rapid decrease with decreasing wind speeds, especially in the crosswind direction. The same response was also seen in the SWADE data collected under low-wind conditions. Combining these data sets and comparing them with the DP87 model, we found much better agreement than with CMOD4, but the DP87 model seemed to predict a sharper rolloff in the backscatter with wind speed than the measurements demonstrated. We accounted for this difference by including the wind direction variability into the DP87 model. From buoy wind measurements, we determined that the standard deviation of the wind direction was inversely proportional to the wind speed, and for a given wind speed, the fluctuation of the wind direction about the upwind direction could be modeled by a Gaussian distribution. Using a Gaussian distribution for the wind direction with a wind speed dependent standard

deviation as measured, we averaged the predicted values of the DP87 model over an area equivalent to CSCAT's resolution. The averaged DP87 predicted response agreed with our measured response. From this we concluded that the rapid decrease in the backscatter is most likely due to viscous dampening as the DP87 predicts. Furthermore, these results also showed that comparisons under low-wind conditions between backscatter measurements of different resolutions or with models, must include the variability of the wind direction. For the case of airborne-satellite comparisons, we demonstrated that by averaging CSCAT measurements over an area equivalent to that of the AMI scatterometer, our measurements agreed with CMOD4, which was developed from the AMI data. These results were published in Jim Carswell's dissertation and we are currently working with our colleague Mark Donelan on a paper addressing these results.

KUSCAT Measurements

In 1996 NSCAT, a NASA satellite-based Ku-band scatterometer, will be launched. To support this instrument, MIRS designed and fabricated KUSCAT, and recently flew it on the NASA WFF research P3 in LITE. This experiment consisted of six missions, over the Atlantic Ocean, dedicated to providing airborne support for the Ladir platform on the space shuttle.

Being KUSCAT's first deployment, these missions served as an engineering test to evaluate its performance. The instrument operated for the entire experiment without any problems, collecting over sixty hours of data. We processed the backscatter measurements, using the SASS-II model, to produce near surface wind vector estimates for the LITE science team. We compared these estimates with wind speed estimates obtained with the NASA Wallops Radar Ocean Wave Spectrometer (ROWES), and found agreement within less than $1 \text{ m}\cdot\text{s}^{-1}$. Additionally, KUSCAT operated in rapid incidence mode providing us with simultaneous backscatter measurements at 20° , 30° , 40° and 50° incidence. We are currently working with Doug Vandemark of NASA Wallops in analyzing the data. Our focus is on a particular flight where we believe the swell was propagating at a different angle than the surface wind direction. The 20° backscatter measurements showed a different directional response than the backscatter at the other three angles. Vandemark's instrument, ROWES, will provide

us with estimates of the directional wave spectra, so that we may further investigate this phenomena.

EMBR Measurements

Range measurements made by satellite-based radar altimeters experience a bias towards the trough of ocean waves. EMBR, designed to study this phenomena at the two frequencies of the TOPEX/POSEIDON altimeter, participated in three measurement campaigns: EM-Bias/SEEP, SWADE and SOWEX.

The EM-Bias/SEEP measurement campaign consisted of six flights off the coast of Virginia during February to April of 1989. EMBR was flown on the NASA WFF research P3, along with the Goddard Space Flight Center (GSFC) surface contour radar (SCR) and airborne oceanographic lidar (AOL). These instruments provided backscatter measurements at 5.3 GHz, 13.6 GHz, 36 GHz and 337.1 nm. The primary goal was to study the frequency dependence of the electromagnetic (EM) bias. Working with Ed Walsh of GSFC, we analyzed the data to determine the EM bias and its dependence on frequency. Our results were published in the November, 1991 issue of the *Journal of Geophysical Research (Oceans)* [9]. The EM bias measurements linearly decreased with increasing radar frequency from 5.3 GHz to 36 GHz. We proposed an empirical relationship describing the frequency dependence. We also found that the EM bias was strongly correlated to the wind speed, increasing as the wind increased. The exact relationship between the wind and EM bias could not be determined due to the limited cases sampled, but the measurements demonstrated that the wind speed was the single most important parameter in modeling the EM bias at all the radar frequencies.

To improve our understanding of the EM bias dependence on wind and wave conditions, we participated in SWADE flying EMBR, in conjunction with NASA GSFC scanning radar altimeter (SRA) and AOL, on the NASA WFF P3 from 17 January 1991 through 4 March 1991. A variety of wind and wave conditions were sampled ranging from $4 \text{ m}\cdot\text{s}^{-1}$ to $12 \text{ m}\cdot\text{s}^{-1}$ winds and 1 m to 6 m seas. Following SWADE, EMBR and the NASA GSFC SRA participated in SOWEX to gather higher wind cases. During this experiment, measurements were acquired at wind speeds up to $20 \text{ m}\cdot\text{s}^{-1}$ and 8-m waves. Collaborating with Mike

Banner, of the University of New South Wales (UNSW), and Ed Walsh, we established an EM bias correction algorithm for the NASA Radar Altimeter on TOPEX/Poseidon. We summarized our results and historic EM bias data in the special TOPEX issue of the IEEE Transactions on Geoscience and Remote Sensing [10]. We also presented these results at the TOPEX/Poseidon Verification Meeting at the JPL. The final correction algorithm was worked out as a consensus between our airborne measurements and on-orbit data analysis performed by other community members. Laszlo Hevizi, who conducted most of the UMass research activities on this project, presented a detail study on the EM bias measurements in his Ph.D. dissertation.

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Publications

This section lists the journal and conference publications that resulted from the research efforts supported by this NASA grant.

Journal Publications

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Conference Publications

- [1] J. R. Carswell, W. J. Donnelly, and R. E. McIntosh, "Investigation of the azimuthal response of off-nadir backscatter from the ocean surface", in *IEEE International Geoscience and Remote Sensing Symposium*, Florence, Italy, July 10-14 1995.
- [2] J. R. Carswell and R. E. McIntosh, "Backscatter from the ocean surface under low-wind conditions", in *IEEE International Geoscience and Remote Sensing Symposium*, Pasadena, CA, August 1994.
- [3] L. Hevizi, R. McIntosh, and E. Walsh, "The radar cross section dependence on the electromagnetic bias", in *Abstracts of the Symposium on the Air-Sea Interface*, Marseilles, France, June 27 1993.
- [4] S. Carson, R. McIntosh, F. Li, S. Nghiem, S. Lou, and G. Neuman, "Comparisons of c and ku band sigma zero measurements with model predictions at low wind speed", in *Abstracts of the Symposium on the Air-Sea Interface*, Marseilles, France, June 25 1993.
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- [6] S. Carson, R. McIntosh, and John Wilkerson (and four other authors), "Intercomparisons of airborne c-band scatterometer measurements with in-situ bouy, aircraft, and satellite surface wind estimates: Initial results and future applications", in *Meteo France Specialty Meeting on Airborne Radars and Lidars*, Toulouse, France, July 1992.
- [7] S. Carson, R. E. McIntosh, F. Li, S. Nghiem, S. Lou, and G. Neuman, "Radar backscatter measurements obtained during the surface wave dynamics experiment (swade)", in *IEEE International Geoscience and Remote Sensing Symposium*, Houston, TX, May 26-29 1992.
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- [12] D. J. McLaughlin, A. Pazmany, E. Boltniew, and R. E. McIntosh, "Sea clutter measurements with a novel c-band scatterometer", in *PIER Symposium Proceedings*, Boston, MA, July 26 1989.
- [13] D. J. McLaughlin, A. L. Pazmany, E. Boltniew, L. Hevizi, and R. E. McIntosh, "An airborne c-band scatterometer for remote sensing the air sea interface", in *IEEE International Geoscience and Remote Sensing Symposium*, Vancouver, BC, July, 10 1989.
- [14] C. D. Massey, F. Lalezari, D. J. McLaughlin, and R. E. McIntosh, "An electromechanically scanned microstrip antenna for airborne applications", in *IEEE AP-S International Symposium*, San Jose, CA, June 26 1989.

Degrees Earned

The research performed for this NASA grant resulted in the following PhD. dissertations and Master's theses:

- [1] J. R. Carswell, *Analysis of Off-Nadir C-Band Backscatter Measurements of the Ocean Surface Under Low-Wind Conditions*, PhD thesis, University of Massachusetts, 1995.
- [2] L. G. Hevizi, *Airborne Measurements of the Electromagnetic Bias*, PhD thesis, University of Massachusetts, 1994.
- [3] S. C. Carson, *Airborne Measurements of Radar Backscatter from the Ocean Surface at C-Band*, PhD thesis, University of Massachusetts, 1993.
- [4] D. J. McLaughlin, *Remote Sensing of the Ocean Surface with C- and Ku-Band Airborne Scatterometers*, PhD thesis, University of Massachusetts, 1989.
- [5] A. Paylor, "A c-band scatterometer for normalized radar cross section measurement", Master's thesis, University of Massachusetts, 1994.
- [6] E. Boltnew, "Design and implementation of a detection subsystem in a c-band scatterometer for topographical imaging of terrain", Master's thesis, University of Massachusetts, 1990.
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- [8] A. L. Pazmany, "Computer aided design of a c-band scatterometer", Master's thesis, University of Massachusetts, 1988.